

Nitrogen, Phosphorus, and Potassium Flows through the Manure Management Chain in China

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Environmental Science and Technology

DOI:

[10.1021/acs.est.6b03348](https://doi.org/10.1021/acs.est.6b03348)

Published: 01/01/2016

Peer reviewed version

[Cyswllt i'r cyhoeddiad / Link to publication](#)

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):

Bai, Z., Ma, L., Jin, S., Ma, W., Velthof, G. L., Oenema, O., Liu, L., Chadwick, D., & Zhang, F. (2016). Nitrogen, Phosphorus, and Potassium Flows through the Manure Management Chain in China. *Environmental Science and Technology*, 50(24), 13409-13418. <https://doi.org/10.1021/acs.est.6b03348>

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Journal:	<i>Environmental Science & Technology</i>
Manuscript ID	es-2016-033488.R2
Manuscript Type:	Article
Date Submitted by the Author:	n/a
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Manuscripts

1 **Nitrogen, phosphorus and potassium flows through the**
2 **manure management chain in China**

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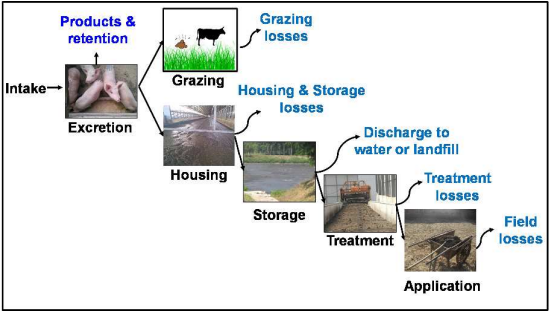
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26

27 **Abstract:**

28 China is the biggest livestock production and largest fertilizer user country in the
29 world. However, quantification of nutrient flows through the manure management
30 chain and their interactions with management-related measures is lacking. Here, we
31 present a detailed analysis of nutrient flows and losses in the “feed intake – excretion
32 – housing – storage – treatment – application” manure-chain, while considering
33 differences between livestock production systems. We estimated the environmental
34 loss from the manure-chain in 2010 to be up to 78% of the excreted nitrogen, and over
35 50% of excreted phosphorus and potassium. Greatest losses occurred from housing
36 and storage stages, via NH_3 emissions (39% of total nitrogen losses), and direct
37 discharge of manure to water bodies or landfill (30-73% of total nutrient losses).
38 There are large differences between animal production systems, where the landless
39 system has the lowest manure recycling. Scenario analyses for the year 2020 suggest
40 that significant reductions of fertilizer use (27%-100%) and nutrient losses (27-56%)
41 can be achieved through a combination of prohibiting manure discharge, improving
42 manure collection and storages infrastructures, and improving manure application to
43 cropland. We recommend that current policies and subsidies targeted at the fertilizer
44 industry should shift to reduce the cost of manure storage, transport and application.

45



INTRODUCTION

Intensive livestock production systems have large impacts on water and air quality through emissions of greenhouse gases (GHG) and nutrients (mainly nitrogen (N) and phosphorus (P))¹⁻⁴. The N and P emissions originate mainly from livestock excrements. Total livestock excretion in the world is about 80-130 Tg N per year, from which only 20-40% is efficiently utilized for fertilizing cropland⁵⁻⁶. The remainder of the manure N excreted is emitted to the atmosphere, groundwater or surface waters. However, there are large differences in manure management throughout the world, depending on livestock production system, environmental conditions and governmental policy measures. For example, on average 65% of excreted N in animal housing is recycled back to agricultural land in the Europe Union (EU), which is in part a result of strict regulations⁷. At the farm level, there can be large differences. A survey in Africa showed that 6-99% of collected manure is recycled cropland⁸. In China, a large proportion of manure N from pig production is lost via direct discharge into water bodies or is landfilled⁹⁻¹⁰.

Recent studies have used material flow and nutrient footprint approaches to quantify N and/or P losses and use efficiencies for whole livestock production systems at global level¹¹, regional level (EU^{12,13}) and national level (United States, USA¹⁴). Several models have been developed to estimate the nutrient flows and losses in livestock production, e.g. MITERRA-Europe¹⁵, NUFER (NUtrient flows in Food chains, Environment and Resources use)¹⁶, and GAINS (Greenhouse Gas–Air Pollution Interactions and Synergies)¹⁷. Some other models have been developed to

68 estimate single pollutant losses from livestock systems, e.g. ammonia (NH_3) losses
69 emission from manure management¹⁸. However, there are no models available yet that
70 can calculate N, P and potassium (K) flows and losses in detail for each step in the
71 “feed intake – excretion – housing – manure storage – manure treatment – manure
72 application” chain in a consistent way for the different animal categories and
73 production systems, at the regional level. A further understanding of the manure
74 nutrient flows and losses is important, because previous studies showed that the
75 effects of feeding regimes and manure management practices strongly differ between
76 livestock production systems^{10,19}. For example, N losses from traditional dairy
77 production systems in China, mainly occur through NH_3 emissions, and in the
78 industrial dairy feedlots mainly through direct discharge of manure to water bodies or
79 landfill¹⁰. Information about the effects of management-related technical measures
80 and their interactions on manure nutrient recycling and subsequent chemical fertilizer
81 needs are still lacking. Such insights are needed for achieving low emission livestock
82 production systems and sustainable agriculture in China²⁰.

83 China is a major contributor to world livestock production, and both extensive and
84 intensive systems exist^{21,22}. Industrial-scale livestock operations are rapidly increasing
85 in their contribution to total livestock production, mainly because of their large
86 production capacity and high feed use efficiency on the farm. However, most of these
87 industrial systems are landless and have limited opportunity to recycle manure
88 nutrients back to crop land. Recently, the Chinese government initiated a plan to
89 stabilize fertilizer consumption by 2020, the so-called “Zero Fertilizer Increasing by

2020” goal²⁰. The consumption of K fertilizers is large²² and there are no studies in which the potential of replacing fertilizer K by manure K has been assessed. The aim of this study was to estimate the manure N, P and K flows and losses in the “feed intake – excretion – housing – storage – treatment – application” chain for different animal categories and production systems in China for the year 2010, using a modified version of the NUFER model. We developed a ‘K module’ and included it in the NUFER model. The analyses were carried out for different animal categories (pigs, layers, broilers, dairy cattle, beef cattle, buffaloes and draught cattle, and sheep and goats) and different production systems (mixed, grazing and landless systems). In addition, five scenarios were explored to assess the potentials for reducing manure N, P and K losses and for replacing fertilizer inputs by manure nutrients for the year 2020.

102

103 MATERIALS AND METHODS:

104 The NUFER model¹⁶ was further developed and used to estimate N, P and K flows
105 and losses in each step of the manure management chain. This model uses a mass
106 balance approach; it starts with an estimation of total feed nutrients intake rate for the
107 different animal categories. The calculation methods and parameters used are
108 presented in detail in the Supplementary Information (SI). Below a summary is given.

109

110 Description of livestock production systems

111 In total, six animal categories and three typical (for China) production systems were

distinguished. The six main animal categories include pigs, layers, broilers, dairy cattle, other cattle (beef cattle, buffaloes and draught cattle), and sheep and goats. Together these categories generate most of the manure in China²³. For each animal category we distinguished three different production systems, according to the feeding regimes, manure management practices and available statistical data, i.e. mixed cropping-livestock system, grazing production system and landless production system (Table S1). Mixed cropping-livestock systems are basically the traditional production system; the solid part of excretion is collected and mainly applied to cereal crops, while the liquid fraction is only partly collected and the remainder is lost by leaching into the subsoil and wider environment. Grazing systems are mainly found in Gansu, Xinjiang, Ningxia, Tibet, and Inner-Mongolia provinces¹⁶, see also Fig S1. Most of the excretion is directly dropped to grassland, during the grazing period. The solid part of the excretion is collected when the animals are kept in confinement; however, the liquid part is mainly leached to the subsoil. The industrial production systems are landless; a large fraction of the manure produced in landless systems is discharged into surface waters, with or without some treatment, or dumped into landfills. A part of the solid manure is exported to nearby farms growing vegetables and fruits following composting treatment. The livestock production structure (i.e. the percentage of each system per animal category) in 2010 was derived from national statistics²¹. Information about the definitions and animal population of each production system is listed in Tables S1 and S2 in the SI.

133

134 **Feed and nutrient intake calculation**

135 Total feed intake was calculated from the number of livestock for each category and
136 the feed requirements per animal category. Feed intake was estimated on the basis of
137 the energy requirements for maintenance, growth (live weight gain) and production
138 (Bai et al. 2013; 2014)^{9,10}. The number of animals per category was derived from
139 MOA statistics²¹ and the FAO database²². For pigs and broilers, the number of
140 slaughtered animals was used, and for dairy and layers, the numbers of producing
141 animals²². Stock numbers were used for beef cattle, buffaloes and draught cattle, and
142 sheep and goat production²². Feed intake was estimated from energy requirements per
143 animal category and feed supply according to data from the FAO database and farm
144 surveys^{16,22}. Feed-specific N, P and K contents were derived from literature (Table
145 S9). The excretion of nutrients was calculated as the difference between feed nutrient
146 intake and the nutrient retained in products (milk, eggs) and in body weight gain
147 (meat, blood, bones and hides).

148

149 **Nutrient retention by livestock**

150 Nutrient (N, P and K) retention was calculated at the herd level per animal category
151 (considering the breeding and backup animals). In a simple form (for one animal
152 category, production system), the equation for estimating retention showed as below:

$$153 \text{ } Oa_{\text{nutrient in products}} = (\text{Yield} + \text{BWG}) * \text{Animal number} * \text{Nutrient content} \quad [1]$$

154 Where, $Oa_{\text{nutrient in products}}$ is the total amount of N, P or K in animal body weight gain,
155 milk and egg, in kg per year; Yield is the yield of animal products (milk and eggs), in

156 kg head⁻¹ yr⁻¹; BWG is the body weight gain of animals, including meat, bones, blood
157 and hides, in kg head⁻¹ yr⁻¹ (Table S5-7); Nutrient content is the N, P or K content of
158 milk, eggs and BWG, in kg kg⁻¹. The N and P contents were derived from the NUFER
159 database¹⁶. The K content was derived from literature (Table S8).

160

161 **Nutrient excretion**

162 Nutrient excretion was calculated as the difference between total nutrient intake and
163 nutrient retention in milk, egg and BWG. In a simple form:

164
$$Oa_{\text{nutrient excretion}} = Ia_{\text{nutrient intake}} - Oa_{\text{nutrient in products}} - Oa_{\text{nutrient in dead animals}} \quad [2]$$

165 Where, $Oa_{\text{nutrient excretion}}$ is the amount of nutrient (N,P and K) excreted per animal
166 category, in kg yr⁻¹; $Oa_{\text{nutrient in products}}$ is the amount of N, P and K output in milk, eggs
167 and BWG per animal category and production systems, respectively, in kg yr⁻¹; and $Ia_{\text{nutrient intake}}$
168 represents the amount of N, P and K in feed intake per animal category and
169 production system, in kg yr⁻¹. Corrections were made for animals that died during the
170 production cycle ($Oa_{\text{nutrient in dead animals}}$); it was assumed that the nutrients in dead
171 animals ended up landfill, possibly following incineration.

172

173 **Nutrient use efficiency and manure nutrient recycling efficiency**

174 The N, P and K use efficiencies and manure nutrient recycling efficiency were
175 calculated at herd level as follows:

176
$$\text{Nutrient use efficiency} = (Oa_{\text{nutrient in products}} / Ia_{\text{nutrient intake}}) * 100\% \quad [3]$$

177
$$\text{Manure nutrient recycling efficiency} = (Oa_{\text{nutrient recycled}} / Oa_{\text{nutrient excretion}}) * 100\% \quad [4]$$

178 Manure nutrient recycling efficiency is the percentage of excreted N, P and K
179 recycled to agricultural land per animal category and production system. Oa_{nutrient}
180 $_{\text{recycled}}$ is sum of the amounts of N, P and K deposited during grazing and applied to
181 agricultural land per animal category and production system, in kg yr^{-1} .

182

183 **Fertilizer replacement by manure**

184 The potential to replace fertilizer by manure was calculated as follows:

$$\begin{aligned} 185 \text{ Fertilizer replacement} &= \{(\text{Manure application} * \text{Fertilizer value}) / \text{Fertilizer} \\ 186 \text{ application}\} * 100\% & \quad [5] \end{aligned}$$

187 Where, Fertilizer replacement is the amount of fertilizer N, P and K that can be
188 replaced by manure N, P and K, in %; Manure application is the amount of manure N,
189 P and K applied to cropland (excluding manure N, P and K deposited during grazing
190 because essentially no fertilizer is applied to grassland in China), in kg yr^{-1} ; Fertilizer
191 value is the proportion of the manure N, P and K available to crops in the first season,
192 in % (Table S13); Fertilizer application is the amount of fertilizer N, P and K applied
193 to cropland in 2020, in kg yr^{-1} . Fertilizer values differ per animal manure type and
194 nutrient. The total fertilizer application in 2020 was estimated from the total N, P and
195 K fertilizer application in 2015²², and the expected increase in fertilizer use during the
196 period 2015- 2020²⁰.

197

198 **Scenarios for 2020**

199 A total of five future scenarios were considered to explore the potential for reducing

200 nutrient losses from the manure management chain and the potential for replacing
201 fertilizer nutrients by manure nutrients, The year 2010 was used as the reference year
202 because of data availability, and 2020 was set as a target year, because of China's aim
203 to achieve "Zero Fertilizer Increase Use" by the end of 2020²⁰. According to the
204 projections by FAO, the total demand for animal products in China will increase by
205 17% for pork and eggs, 33% for chicken meat, 24% for milk, 24% for beef, and 22%
206 for mutton²⁴ between 2010 and 2020.

207 **S0 – Business as usual (BAU).** Production of animal products was based on linear
208 extrapolations of the projections of FAO between 2010 and 2020²⁴. In this scenario,
209 we assumed that the increase in the demand for livestock products would be produced
210 in land-less systems. We also assumed that the productivity, feed composition and
211 manure management practices of each system would be the same as in 2010, which
212 may provide a conservative estimate of manure nutrient production, flows and losses.
213 Changes in animal numbers between 2010 and 2020 are shown in Table S2.

214 **S1 – Prohibit the discharge of manure.** This scenario builds on S0, but includes an
215 adoption of stricter manure management regulations²⁵. We assumed that the discharge
216 of manure to surface water or landfill will be prohibited in the industrial animal
217 production systems.

218 **S2 – Improving manure collection and nutrient preservation in housing and**
219 **storage systems.** This scenario builds on S0, and assumes in addition that the N
220 losses (in % of excreted N) from animal housing and storage systems will decrease to
221 current mean levels in the European Union (EU), i.e., the average N losses via NH₃,

222 N₂O and N₂ emissions to air and via N leaching will decrease to 5%, 1%, 5% and 0%
223 of the amount of manure N excreted, respectively²⁶. Further, there will be no losses of
224 manure P and K from industrial production system due to improved containment of
225 manures.

226 **S3 – Improving manure application.** This scenario builds also on S0. Current crop
227 production in China does not account for nutrients supplied by manure, especially in
228 cash crop production (e.g. in greenhouse vegetables and orchards) in which the
229 amounts of nutrient applied with fertilizer and manure far exceed the nutrient demand
230 of the crop²⁷. We assume that the available nutrients in manures applied to cropland
231 replace fertilizer nutrients, using manure-specific fertilizer nutrient replacement
232 values. Further, we assumed that low ammonia emission manure application methods
233 will be adopted, i.e. slurry injection and rapid incorporation of solid manures, by
234 which the N fertilizer replacement value of manures will increase to 55% for cattle
235 slurry, 75% for pig slurry and 85% for poultry manure (Table S13).

236 **S4 – Combination of S1-S3.** In this scenario, the technologies assumed for S1, S2
237 and S3 are combined. Further, we assumed that the technologies can be applied as
238 complements to each other.

239

240 RESULTS

241 Nutrient flows through the whole manure chain

242 The N, P and K flows in the manure chain for the year 2010 are presented in Fig 1.

243 Total feed N intake amounted to 26.0 Tg, from which 22.8 Tg N was excreted (3.5 Tg

244 N was deposited in the field during grazing and 19.3 Tg N was excreted in housing
 245 systems). Total N losses via NH₃ emission, denitrification, and leaching from housing
 246 amounted to 8.3 Tg. In addition, a significant amount (5.4 Tg N) was lost via
 247 discharge to water bodies or landfill. The collected manure (5.6 Tg N) was treated (by
 248 composting, digestion or separation), which led to another N loss of 1.6 Tg. In total,
 249 only 4.0 Tg manure N was applied to cropland, i.e., 68% to cash crops and 32% to
 250 cereals crops. Total N losses via gaseous emissions, leaching, runoff and erosion
 251 during grazing and after manure application were estimated at 1.5 Tg. The remaining
 252 manure N was either taken up by crops or accumulated in the soil. In total 78% (17.8
 253 Tg N, including field losses) of the excreted N was lost to the environment from the
 254 different stages of the manure management chain. The highest losses occurred from
 255 housing and manure storages (47% of total N loss), followed by discharge of manure
 256 to water bodies or landfill (30%), losses during treatment (9%) and losses following
 257 manure application (8%) and grazing (6%).
 258 About 50% of the total amount of excreted P (4.6 Tg) and 53% of the total amount of
 259 excreted K (16.2 Tg) were recycled in pastures and cropping systems. Similar to N,
 260 cash crops received the highest amount of manure P. However, the applied manure K
 261 was more evenly distributed between grassland, cereals and cash crops, as most of the
 262 K came from other cattle, and sheep and goat production (Fig 2, 3)

263

264 **Contributions of different animal categories and production systems**

265 Fig 2 presents the relative contributions of different production systems and animal

categories to total manure nutrient flows and losses. Clearly, the manure nutrient flows were largest in the mixed production systems, accounting for 53%-57% of total nutrient excretion. Nutrient excretion was smallest in grazing systems. Nutrient recycling was smallest in the landless production system and largest in grazing systems. The P losses were relatively low in grazing systems (3% of total manure P losses), and high in mixed and landless production systems. Manure production was highest for the category beef cattle, buffaloes and draught cattle, followed by sheep and goats and then pigs. Pigs excreted two times more P than sheep and goats. The contributions of layers, broilers and dairy cattle to manure nutrient flows were relatively small (Figure 2).

276

277 **Nutrient use efficiencies at herd level**

The average feed nutrient use efficiency at herd level, across all livestock categories, was 11% for N (NUE), 14% for P (PUE), and 2.7% for K (KUE). The low KUE was related to the low K contents of meat, milk and egg. The landless production systems had much higher nutrient use efficiencies than the other two production systems (Figure 3a). For example, the NUE of landless systems was 21%, almost six times that of grazing systems. The mixed production system was more efficient than the grazing system to convert feed N and K into products (Figure 3a), but the grazing system had a higher PUE than the mixed system.

The NUE at herd level was highest for broilers (40%) and lowest for beef cattle, buffaloes and draught cattle (2.3%). Similar results were found for PUE and KUE.

288 The monogastric animals (broilers, layers and pigs) were more efficient than the
289 ruminant livestock categories (dairy cattle, beef cattle, buffaloes and draught cattle,
290 sheep and goats) in utilizing feed nutrients (Fig 3b).

291

292 **Manure nutrient recycling efficiency**

293 The manure N recycling efficiency decreased in the order of grazing (54%) > mixed
294 (34%) > landless (19%) production system. Similar trends were found for manure P
295 and K recycling efficiencies (Figs. 3c and 3d). The manure nutrient recycling
296 efficiency of grazing systems was about two times greater than that of the landless
297 system (Fig 3c). The manure nutrient recycling efficiency ranged from 20 to 40% for
298 N, 30 to 62% for P, and 30 to 65% for K, depending on animal category and
299 production system. The manure nutrient recycling was higher for ruminant animals
300 than for monogastric animals (Fig 3).

301

302 **Losses of nutrients from the manure management chain**

303 Total N losses from the whole manure management chain amounted to 17.8 Tg in
304 2010 (Fig 4). Emission of NH₃ (6.9 Tg; 13 kg N ha⁻¹ agricultural land) and discharge
305 of manure to surface waters or landfill (5.4 Tg, 11 kg N ha⁻¹ agricultural land) were
306 the major N losses pathways. Losses via leaching, runoff and erosion (L&R&E)
307 amounted to 3.4 Tg N (6.6 kg N ha⁻¹ agricultural land). Losses via denitrification and
308 N₂O emissions were 1.8 (3.5 kg N ha⁻¹ agricultural land) and 0.3 Tg (0.5 kg N ha⁻¹
309 agricultural land, respectively. Direct discharge of manure to water bodies or landfill

310 contributed 78% to the total manure P losses and 61% to the total manure K losses.
311 The total average N loss was 35 kg N ha⁻¹ cropland. Average P and K losses were
312 5.0kg P ha⁻¹ and 16 kg K ha⁻¹ cropland, respectively.
313 Animal production systems differed in nutrient loss pathways (Fig 4). Most of the N
314 losses via NH₃, N₂O and N₂ emissions to air, and via leaching, runoff and erosion to
315 water bodies occurred in mixed production systems. Direct discharge of manure into
316 watercourses or landfill represented the largest N loss pathways in landless production
317 system, while there was no discharge of manure nutrient in grazing systems.
318 Ammonia emissions were the largest N loss pathway in mixed systems. Highest P
319 losses were found in pig and poultry production and in landless production systems.
320 Monogastric animals contributed around 50% to the N losses via direct discharge,
321 while ruminant animals were the dominant source of N losses via leaching, runoff and
322 erosion.

323

324 **Scenarios for 2020**

325 In the S0-business as usual scenario, manure management contributed to reduce 1%
326 of N fertilizer, 12% of P fertilizer, and 34% of K fertilizer (Fig 5). The changes in
327 fertilizer replacement are relatively small in the scenario where direct discharge of
328 manure was prohibited (S1). This is because most of the recycled manure was applied
329 to cash crops; these crops are over-fertilized and more manure does not affect the
330 fertilizer use. Also, a ban on direct discharge is not easy to implement, as it will
331 require additional investments in manure storage, transportation and spreading

332 infrastructure, thus increasing the cost. Improving manure collection in housing and
333 storage systems (S2) has also little impact on fertilizer replacement rates, for similar
334 reasoning (Fig S2). Improving manure application strategies (S3) seems more
335 promising than the other two single options; it increases the N fertilizer replacement
336 to 11%, the P fertilizer replacement to 43% and K fertilizer replacement to 76%.
337 In S0, the total N losses from the whole manure management chain will increase by
338 15% in 2020 compared with 2010. The total P and K losses will increase by 12% and
339 22%, respectively (Fig 5b). In all single options, S1 is more effective than S2 and S3
340 in reducing nutrient losses. The N losses can be reduced by 14%, P losses by 47% and
341 K losses by 40% through the prohibition of direct discharges of manure to surface
342 water or landfill and the application of manure to agricultural land. The integrated
343 option (S4) is more effective than the single options, both in reducing fertilizer input
344 and reducing manure nutrient losses. In the combination scenario (S4), 27% of the
345 chemical N fertilizer, 86% of the chemical P fertilizer and all of the chemical K
346 fertilizer can be replaced by optimizing the management of manure. At the same time,
347 manure N losses can be reduced by 27%, P losses by 56% and K losses by 53%,
348 compared with those in the S0 scenario (Fig 5).

349

350 **DISCUSSION**

351 This is the first study on N, P and K flows through the whole manure management
352 chain of different livestock categories and production systems in China, that
353 quantifies the impacts of management and technical measures to reduce N, P and K

354 losses. In 2010, 33 % of the excreted N, 50% of excreted P and 53% of excreted K
355 were recycled, with the rest being lost to the environment at different stages of the
356 manure chain. In contrast to many other countries in the world, the greatest losses
357 occurred via direct discharge of manure to watercourses and landfill. Highest nutrient
358 losses occurred in mixed production systems with other cattle (beef and draught cattle
359 and buffaloes). The results of this study indicate the key stages (animal housing and
360 manure storages), production systems (landless systems) and livestock categories
361 (other cattle and pigs) where policy and research on manure management should be
362 focused in China in the future.

363 Through analysis of the impacts of management-related technical measures, we found
364 that significant reductions of nutrient losses (27-56%) and inputs of fertilizers
365 (27%-100%) could be achieved by 2020. To achieve such reductions, policies for
366 prohibiting direct discharge of manures into watercourses and landfill, improving
367 manure collection and storage infrastructure, and improving manure application
368 methods should be coordinated in the future. The main uncertainties in the results of
369 this study are related to the robustness of the statistical and literature data and the
370 emission factors used. Additional farm level monitoring and measurements of nutrient
371 losses are needed in the future to estimate the nutrient flows more accurately, e.g.
372 gaseous emissions and leaching of nutrients from different livestock systems, and
373 fertilizer replacement values of different manures.

374

375 **Manure nutrient excretion, losses and recycling in China**

Our estimate of total N excretion in 2010 (22.8 Tg) was higher than the net N excretion of some other studies, such as 16 Tg N in 2010²³, 17 Tg N in 2005²⁸, and 19 Tg N in 2005¹⁶. These other studies presented the net excretion only, i.e., they corrected the total excretion for gaseous N losses in housing and storages^{16, 23, 28}. The average gross N and P excretions per animal category were rather similar to reported gross nutrient excretion rates for the EU²⁹ (Table S17). Total excretion was 4.6 Tg for P and 16.2 Tg for K in 2010, which is rather similar to those of previous studies, i.e. 5.2 Tg P in 2010²³, 4.4 Tg P in 2005¹⁶, and 14 Tg K in 2005²⁸. The estimated NH₃ emissions (6.9 Tg NH₃-N) and N₂O emissions (0.3 Tg N₂O-N) were higher than the estimates of other studies (5.3 Tg NH₃-N in 2006³⁰, and 0.2 Tg N₂O-N in 2007³¹). These differences are partly because net N excretion (excluding gaseous N losses from housing) was used in one of the previous studies, and partly because N losses following manure application were not included in the other study²³. In our study, 7.5 Tg manure N (representing 33% of excreted N) was either deposited in grassland by grazing livestock, or applied to cropland (Fig 1). This amount is similar to estimate provided in the study of Ma et al (2010)¹⁶, who reported that 32% of the excreted N was recycled in 2005, but lower than that of Liu et al (2010)²⁸, who reported that more than 50% of the excreted N was recycled in 2002. The latter study did not consider N losses in all stages of the manure management chain and therefore overestimated the amount of manure recycled. About 50% of the excreted P was recycled, which is similar (45%) to that reported by Liu et al (2016)³². Our results suggest that around 8.7 Tg K was recycled, out of the 16 Tg K excreted in 2010.. A

398 nearly similar amounts of K excreted was lost via direct discharge of manure to water
399 bodies or landfill (61%) and leaching to the sub-soil (39%). Leaching coefficient for
400 K were derived from composted manure (Table S12), and applied to the housing,
401 storage and treatment sector for the other manure types of manure, due to lack of data.
402 As composted manure contains relatively lower K in solution, our estimation for K
403 leaching may be relatively low.

404

405 **Comparison with manure management in other countries**

406 About 33% of the excreted N and 50% of the excreted P were utilized in China in
407 2010 (Fig 1). Table 1 shows that these percentages were smaller than those reported
408 for USA (75% of the manure N and P is recycled^{33,34}, the EU (80% of the manure N
409 and almost 100% of the manure P is recycled^{12,35}), and Japan (70% of the manure N
410 and 80% of the manure P is recycled^{36,37}). The differences between China and these
411 other countries are mainly related to environmental regulations. Manure storage and
412 application to agricultural land is regulated in the EU (e.g. Nitrates Directive, Water
413 Framework Directive, and National Emission Ceiling Directive)⁷. The Nitrates
414 Directive regulates the use of N in agriculture, especially through designation of
415 "Nitrate Vulnerable Zones" and establishment of Action Plans in these areas, e.g. the
416 maximum N applied via livestock manure shall not exceed $170 \text{ kg}^{-1} \text{ ha}^{-1} \text{ yr}^{-1}$, and
417 there are 'closed periods' for manure and fertilizer applications, and obligation for
418 leak-tight manure storages with storage capacity per farm of 6-9 months³⁸. The
419 zero-discharge manure systems in USA regulate for manure storage, land application

420 and whole-farm nutrient management planning, resulting in a higher manure recycle
421 efficiency than in China^{39,40} (Table 1). Incentives and taxes can have an important role
422 within some of these policies; for example excess phosphate on farms in the
423 Netherlands was taxed at 9.08 euro for each additional kilogram that exceeds a
424 defined limit⁴² until 2006. However, until a new policy was initiated in 2014, to control
425 the environmental problems resulting from industrial livestock production systems²⁵,
426 there has been little in the way of manure regulations in China. Direct discharge of
427 manure to water bodies is still a major loss pathway. Discharge of manure is forbidden
428 in the EU and USA because of the implementation of the Nitrates Directive in EU⁴²
429 and specific member states resolutions⁴³ and USA federal regulations^{39,40}. Current
430 policies in China mainly focus on manure processing and treatment, to promote
431 recycling of manure⁴⁴. However, our results show that the amount of manure that is
432 treated and subsequently applied to crops only represents a small part of the excreted
433 amount of nutrients (Fig 1). Hence, the effectiveness of these policies is still low.

434

435 **Implications for future manure management**

436 Grassland is extensively managed in China, barely receiving any fertilizers. Hence,
437 improved recycling of manure from animal confinement in grazing systems will not
438 replace fertilizer, but yet may improve pasture production. In contrast, fertilizer and
439 manure P application rates of 261 and 310 kg P ha⁻¹ year⁻¹ have been reported for
440 greenhouse vegetable production systems²⁷. Although production is high in these
441 systems, the high fertilizer applications rates suggest that manure applied to these

442 cash crops did not replace much fertilizer. Only manure nutrients applied to cereal
443 crops were considered to replace fertilizer nutrients in this study. Yet, there is a large
444 potential for replacing fertilizer NPK by manure NPK.

445 In 2020, the total nutrient excretion will amount to 26 Tg N, 5.2 Tg P and 19 Tg K.
446 Results presented in Fig 5 indicate that the objectives of “Zero Fertilizer Increasing by
447 2020” can be achieved, and that fertilizer use can be reduced by 27% for N, 82% for P
448 and 100% for K if the integration of manure management options (S4) can be
449 implemented successfully. Even more fertilizer can be saved if over-fertilization is
450 decreased through the implementation of balanced fertilization⁴⁵.

451 Recycling of manure is not only environmentally beneficial, through the mitigation of
452 nutrient losses, it is also economically profitable. The annual value of manure nutrient
453 in China is equivalent to 190 billion Yuan (roughly 25 billion Euros), based on the
454 prices of N, P, and K in fertilizers²³, and the availability of N, P and K present in
455 animal manure. However, the cost to manure application to crop land is higher than
456 the cost of fertilizer application. In 2015, around 100 billion Yuan of subsidies
457 (equivalent to 13 billion Euros), was provided to the fertilizer industry in China.
458 Redirecting these subsidies for the fertilizer industry towards manure storage
459 infrastructure, manure transportation and manure application would promote more
460 sustainable use of manure nutrients in the future.

461 There are also other barriers to recycling manures nutrients to agricultural land
462 effectively and hence reduce losses, e.g. the lack of information about manure nutrient
463 contents and their bioavailability, a shortage of machines to transport and apply

464 manure, the in-efficient extension services²³, and poor infrastructure in terms of
465 housing and storage systems. More studies are required to improve the accuracy of the
466 estimations of nutrient losses and nutrient efficiency in the whole manure chain. In
467 particular, information is needed on the fertilizer replacement value and nutrient
468 availabilities of different manure types applied to the major crops in typical soil and
469 climates in China, to provide the evidence base for a manure management
470 recommendation system. Further investments are needed to improve the infrastructure
471 and management of the farms.

472 Extensive livestock systems are generally found in remote areas in China, e.g. in
473 Northwest where land degradation is serious, in part because of overgrazing⁴⁷.
474 Intensive livestock production tends to cluster in locations with cost advantages (often
475 close to cities) where insufficient land is available for the recycling of waste from
476 livestock. This may lead to an overload of manure nutrient in these regions. A regional
477 specific analysis is needed to propose region-specific strategies, for effective manure
478 use and mitigation of nutrient losses⁴⁸. There are also other potential environmental
479 problems related to manure management, e.g. antibiotics and heavy metals are of
480 concern. Residues of veterinary antibiotics have been detected in manures and surface
481 water around livestock production farms^{49,50}, and even in the urine samples of
482 children⁵¹. These problems should also be considered through manure chain
483 management strategies.

484 To conclude, only 33% of the excreted N is recycled, which is less than has been
485 estimated in previous studies. Further, 78% of the excreted N by livestock in China is

lost to the environment (including losses after manure application to land, accounted for 11% of total N excretion). Nutrient use efficiencies and manure recycling efficiencies differed greatly between systems and animal categories. There is considerable potential to reduce NPK losses from the manure management chain, and to increase the amount of manure applied to crop land and replace fertilizer NPK through adopting integrated options. However, to improve manure utilization, large changes and investments to livestock farm infrastructure, i.e. animal housing, manure storage, and facilities for manure transportation and application, are needed. An integrated manure and fertilizer nutrient recommendation system has to be developed that takes account of the total nutrient and available nutrient content of manures. Finally, the improved knowledge needs to be disseminated to farmers. .

497

498 **ACKNOWLEDGMENTS**

This work was financially supported by the National Natural Science Foundation of China (31572210), the Hundred Talent Program of the Chinese Academy of Sciences, President's International Fellowship Initiative, PIFI of the Chinese Academy of Science (2016DE008 and 2016VBA073), the UK-China Virtual Joint Centre for Improved Nitrogen Agronomy (*CINAg*) funded by the Newton Fund via UK BBSRC/NERC (BB/N013468/1). DC also acknowledges SAIN for supporting his contribution.

506

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666

667 Table 1. Manure nitrogen (N) and phosphorus (P) excretion, utilization in crop land,
668 and losses in United States of America (USA), Europe (EU), Japan and China.

Year	USA		EU		Japan		China**	
	2002 ³³	2007 ³⁴	2000 ¹²	2000 ³⁵	2005 ³⁶	2005 ³⁷	2010	2010 [·]
	N	P	N	P	N	P	N	P
Excretion (Tg)	6.8	1.7	10.4	4.2	0.73	0.19	22.8	4.6
Utilization (Tg)	5.0	1.3	8.4	4.2	0.51	0.15	7.5	2.3
Losses (Tg)*	1.8	0.4	2.0	0.01	0.23	0.04	15.3	2.3

669 *Not including losses after manure application to crop land.

670 **This study.

671

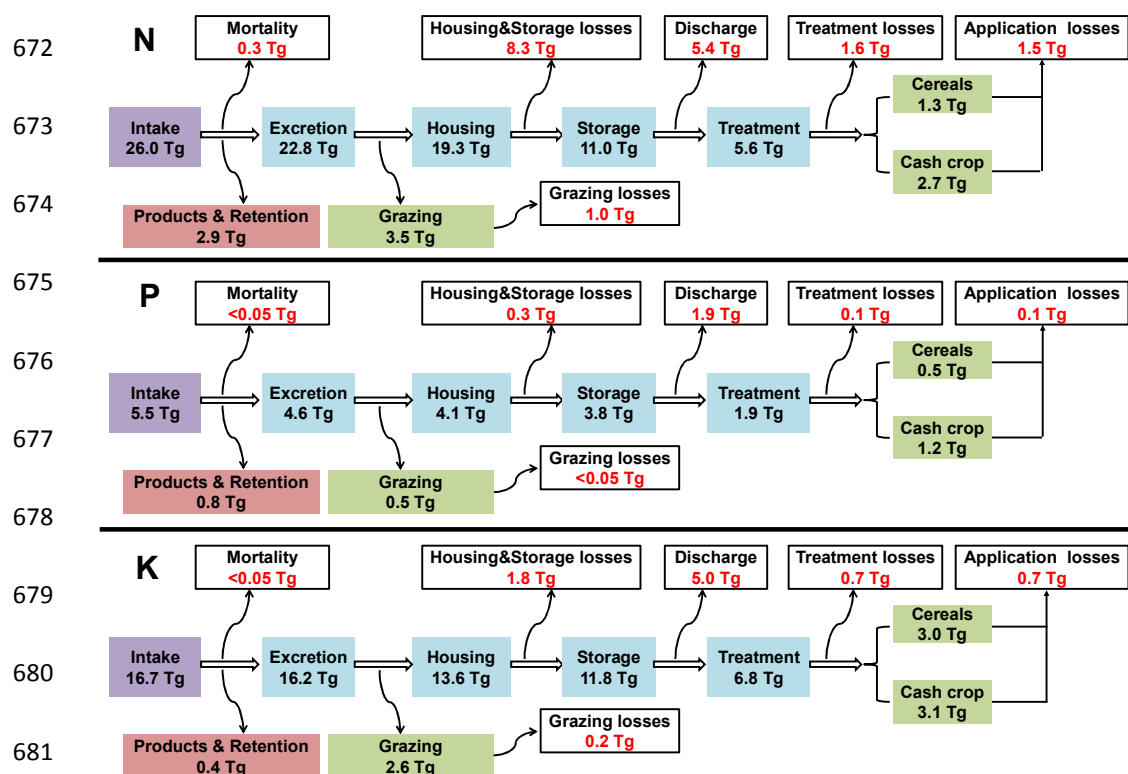
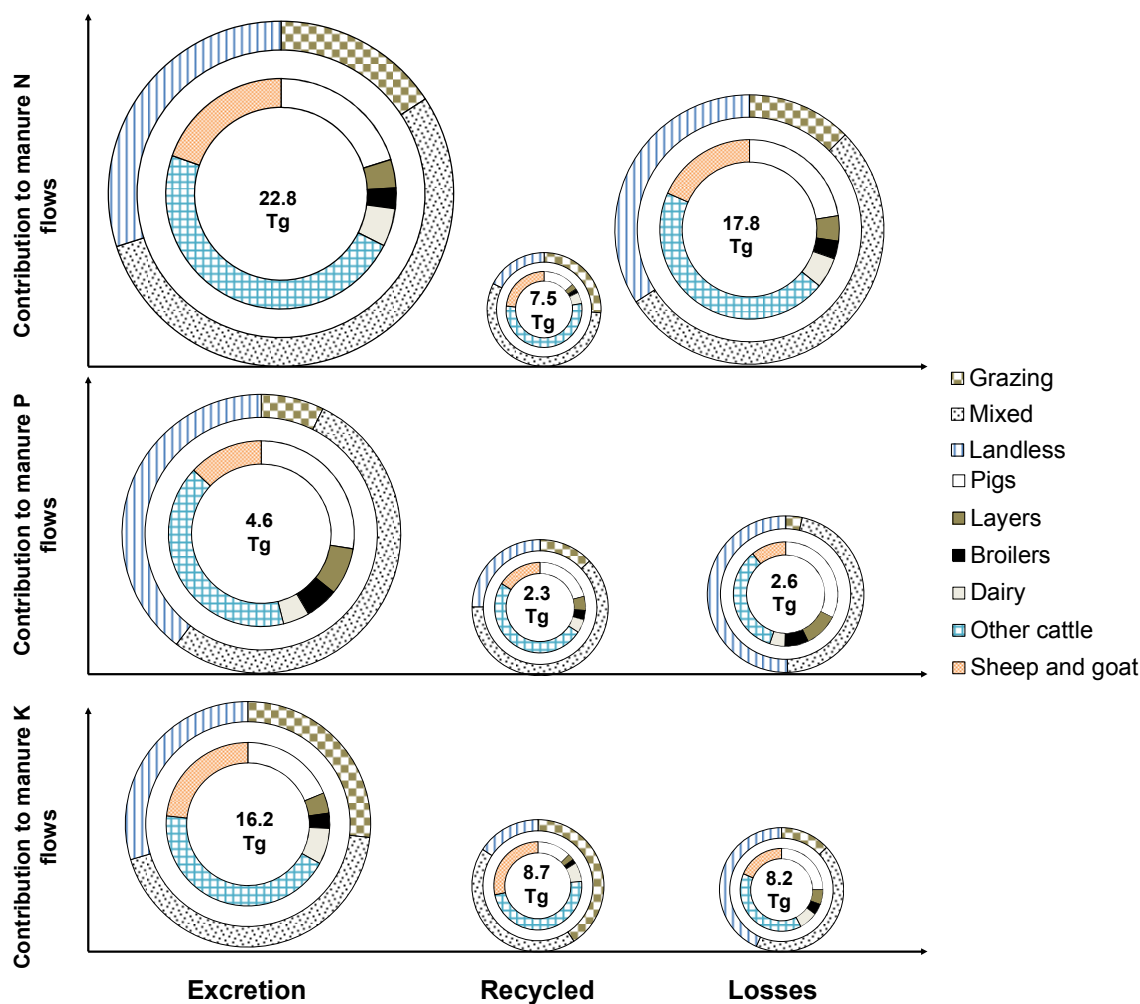


Figure 1. The nitrogen (N), phosphorus (P) and potassium (K) flows through the manure management chain in China in 2010.

Discharge, direct discharge of manure to water body or landfill.



699 Figure 2. The relative contribution of different animal production systems (outside
700 circle) and animal categories (inner circle) to the total manure nitrogen (N),
701 phosphorus (P) and potassium (K) excretion, recycling to agriculture land and losses
702 to the environment from livestock production in China in 2010.
703

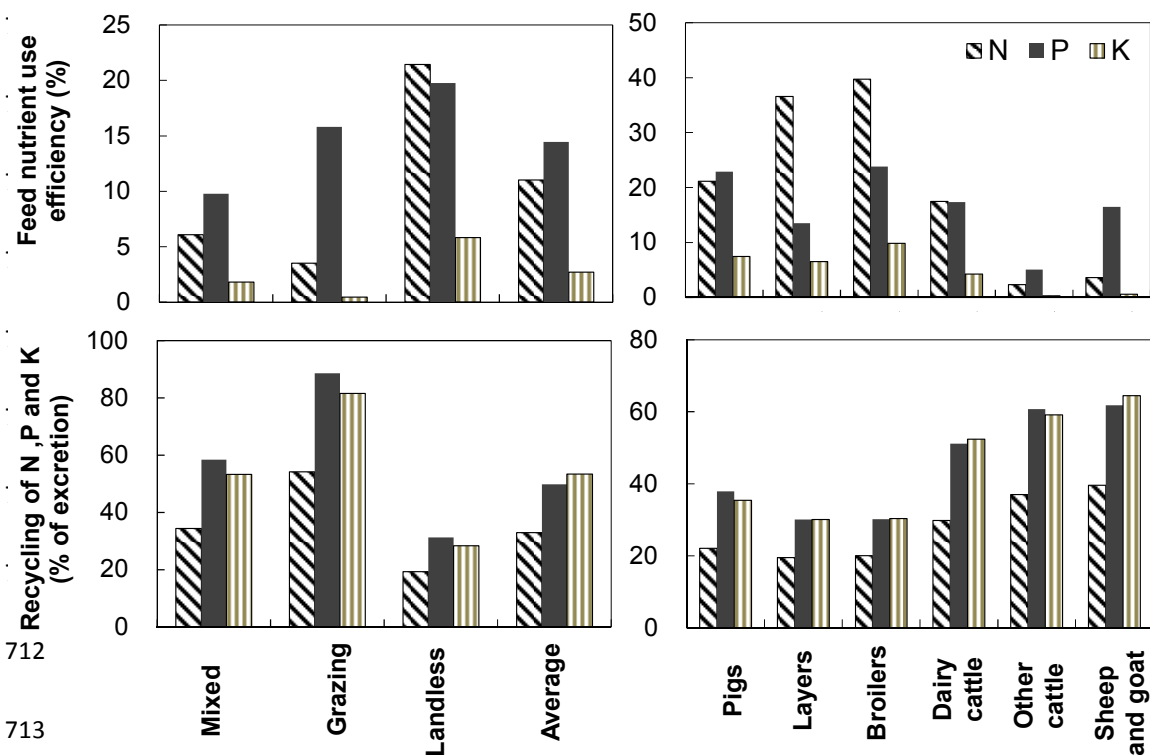


Figure 3. The nitrogen (N), phosphorus (P) and potassium (K) use efficiencies at the herd level for different production systems (a), and animal categories (b), recycling rate of excreted N, P and K for different production systems (c), and animal categories (d).

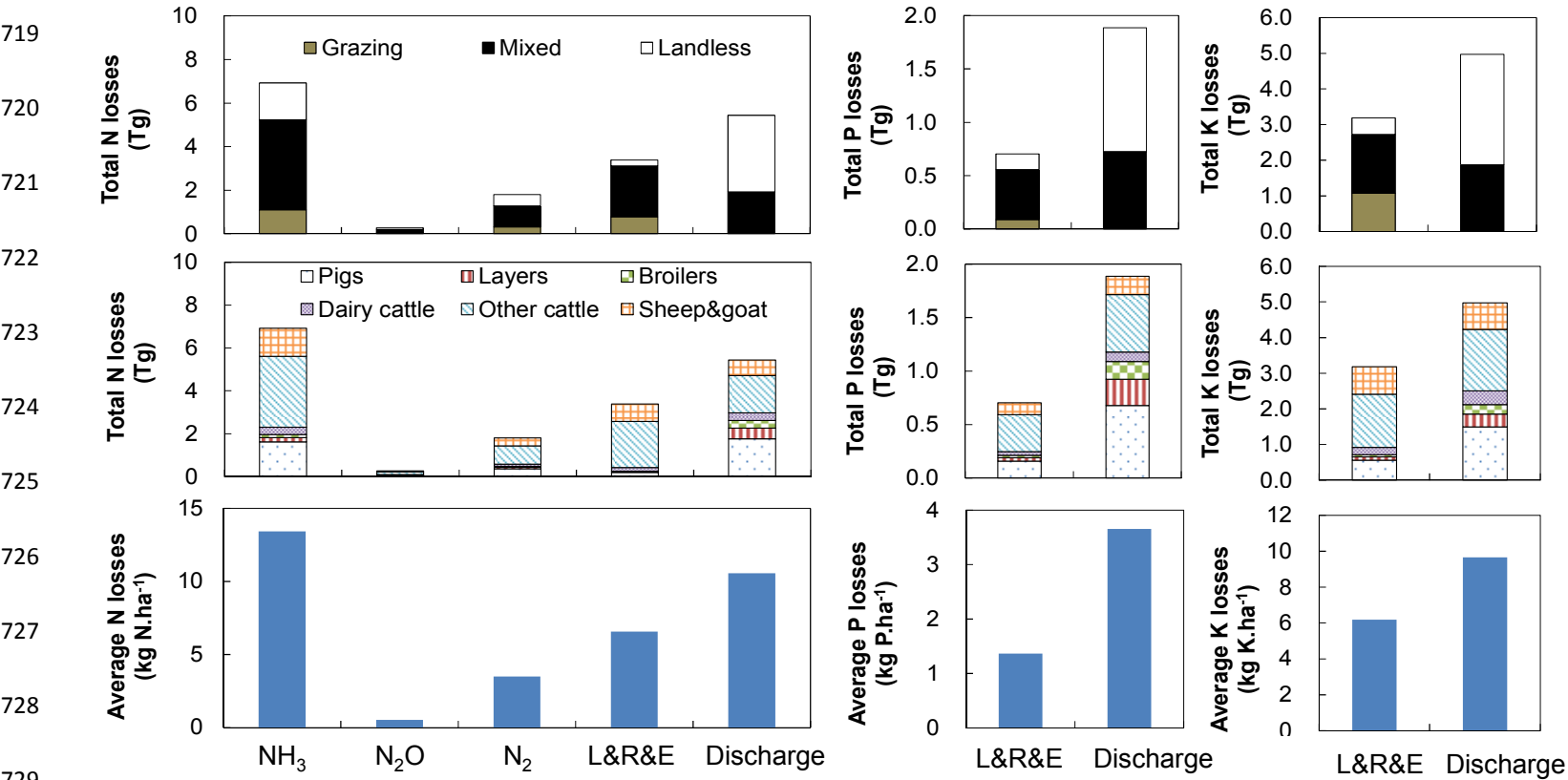


Figure 4. The contribution of the different animal categories and production systems to the total nitrogen (N), phosphorus (P) and potassium (K) losses through the manure management chain in China in 2010, and different scenarios in 2020. *L&R&E are losses by, leaching, runoff and erosion.*

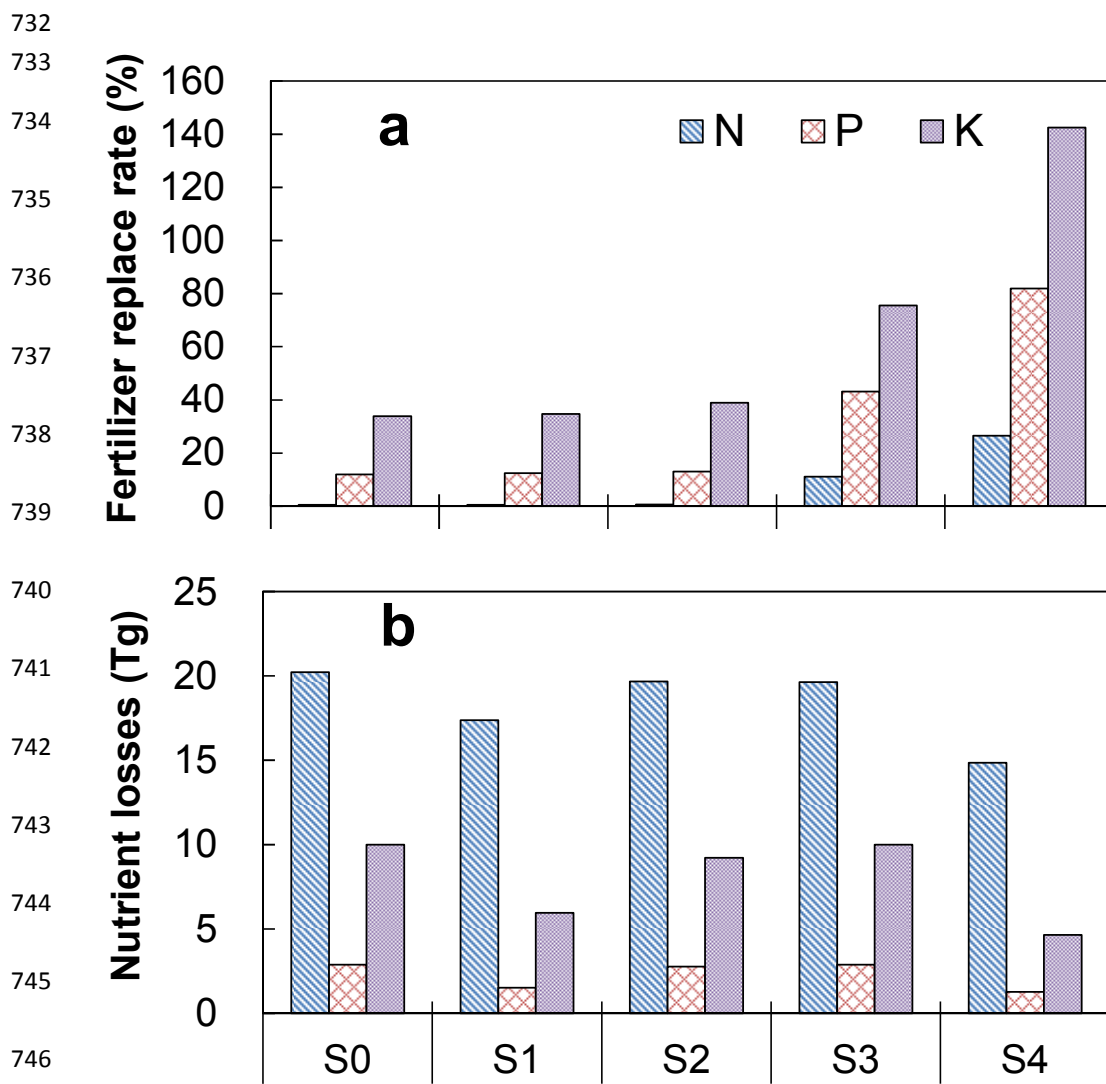


Figure 5. The chemical nitrogen (N), phosphorus (P), and potassium (K) fertilizer replacement by manure (a), and N, P and K losses in the manure management chain (b) in different scenarios in 2020.

S0, business as usual in 2020; S1, promote application of manure and prohibit discharge of manure; S2, improving manure collection in the housing and storage; S3, improving manure application; S4, Combination of S1-S3.